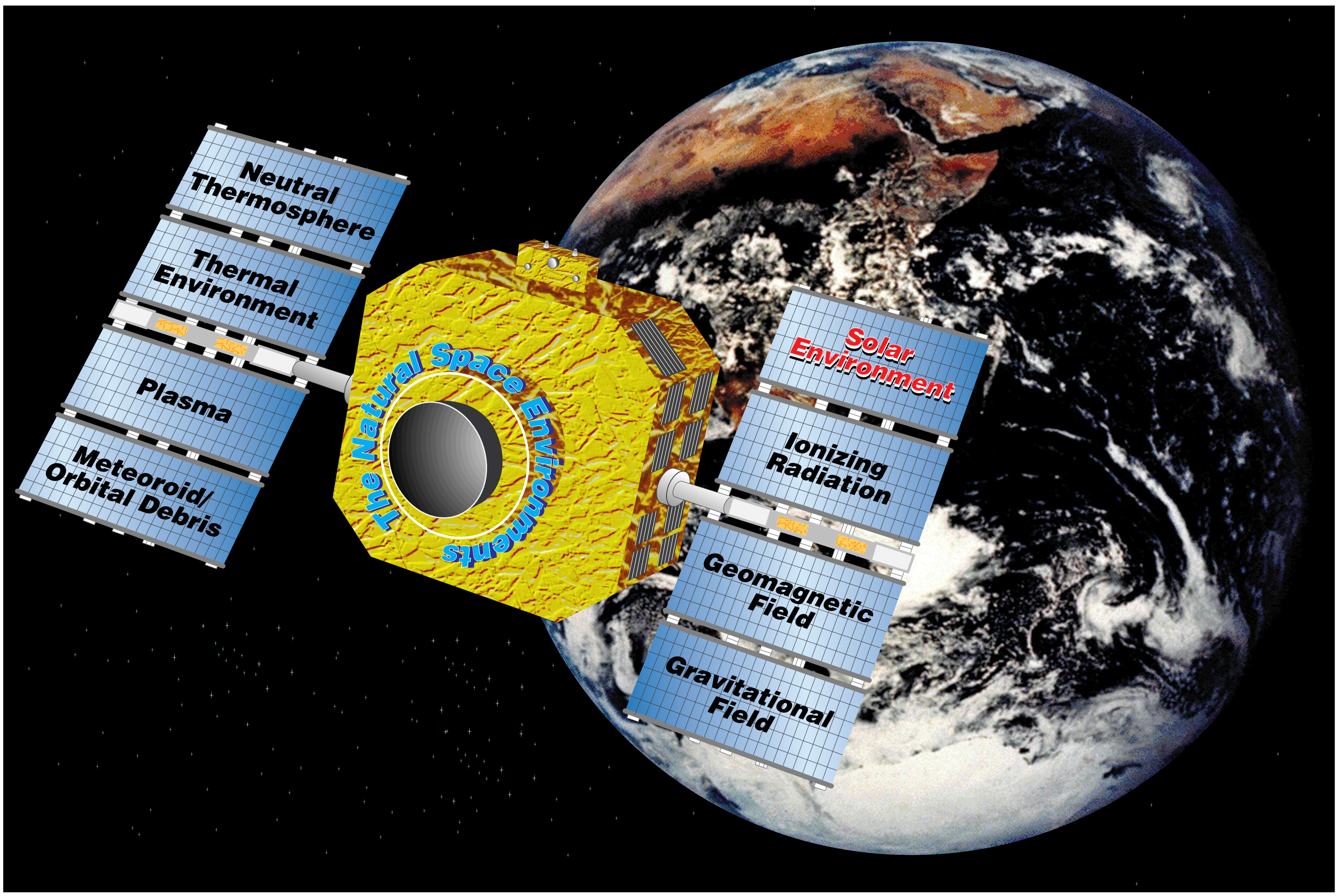
NASA Reference Publication 1396

Spacecraft Environments Interactions: Solar Activity and Effects on Spacecraft

W.W. Vaughan, K.O. Niehuss, and M.B. Alexander



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Spacecraft Environments Interactions: Solar Activity and Effects on Spacecraft

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PREFACE

The effects of the natural space environment on spacecraft design, development, and operation are the topic of a series of NASA Reference Publications* currently being developed by the Electromagnetics and Aerospace Environments Branch, Systems Analysis and Integration Laboratory, Marshall Space Flight Center. The objective of this series is to increase the understanding of natural space environments (neutral thermosphere, thermal, plasma, meteoroid and orbital debris, solar, ionizing radiation, geomagnetic and gravitational fields) and their effects on spacecraft, thereby enabling program management to more effectively minimize program risks and costs, optimize design quality, and achieve mission objectives.

This primer, sixth in the series, describes the interactions between a spacecraft and the space environment resulting from the influence of solar activity. Under certain conditions, these interactions result in significant effects on the performance of a spacecraft. Thus, this publication describes some of these effects and presents key solar activity elements of the solar environment responsible for them.

See NASA RP 1350 for an overview of eight natural space environments (including solar environment-solar activity) and their effects on spacecraft.

* NASA Reference Publications Natural Space Environments Series, available from the Marshall Space Flight Center Electromagnetics and Aerospace Environments Branch, include the following:

"The Natural Space Environment: Effects on Spacecraft," James, B.F., Norton, O.A., Jr., and Alexander, M.B., November 1994, NASA RP 1350.

"Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging," Herr, J.R., and McCollum, M.B., November 1994, NASA RP 1354.

"Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference," Leach, R.D., and Alexander, M.B., July 1995, NASA RP 1374.

"Failures and Anomalies Attributed to Spacecraft Charging," Leach, R.D., and Alexander, M.B., August 1995, NASA RP 1375.

"Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment," Bedingfield, K.L., Leach, R.D., and Alexander, M.B., August 1996, NASA RP 1390.

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INTRODUCTION

The natural space environment refers to the environment as it occurs independent of the presence of a spacecraft; thus, included are both naturally occurring phenomena such as atomic oxygen (AO) and atmospheric density, ionizing radiation, plasma, etc., and a few man-made factors such as orbital debris.[1] Solar activity, manifested in the emission by the Sun of significant amounts of mass and energy, affects the local solar environment and the extended solar environment in terrestrial space. Figures in the appendix of this document list the natural space environments (including solar environment-solar activity) and major areas of interaction with spacecraft systems.

Understanding the natural space environments and their effects on spacecraft enables program management to more effectively optimize the following aspects of a mission:[1]

- Risk—Increasingly, experience on past missions is enabling NASA to provide statistical descriptions of important environmental factors, thus enabling the manager to make informed decisions on design options.
- Cost—Selection of design concepts and mission profiles, especially orbit inclination and altitude, which minimize adverse environmental impacts, is the first important step toward a simple, effective, high-quality spacecraft design and low operational costs.
- Quality—New environment simulators and models provide effective tools for optimizing subsystem designs and mission operations.
- Weight—Consideration of environmental effects early in the mission design cycle helps to minimize weight impacts at later stages. For example, early consideration of directionality effects in the orbital debris and ionizing radiation environments could lead to reduced shielding weights.
- Verification—A unified, complete environments description coupled with a clear mission profile provides a sound basis for analysis and test requirements in the verification process and eliminates contradictory, unnecessary, and incomplete performance assessments.
- Science and Technology—The natural space environment is not static. Not only is our understanding improving, but also new things occur in nature that have not been observed before (for example, a new transient radiation belt recently encountered). Perhaps more importantly, engineering technology is constantly changing and with this, the susceptibility of spacecraft to environmental factors. Early consideration of these factors is key to converging quickly on a quality system design and to successfully achieving mission objectives.

This primer provides an overview of the solar environment and the key role it plays regarding the space environment relative to the design and operation of spacecraft for low-Earth and geosynchronous orbits and deep space trajectories. An understanding of the scope and role of solar activity is needed because its effects are a serious engineering concern for spacecraft operating in terrestrial space.

The region of terrestrial space (fig. 1) extends from the base of the ionosphere (about 60 km above the surface of the Earth) to the boundary of the magnetosphere beyond which interplanetary space is unaffected by the Earth.[3] This distance is about 95000 km above the surface of the Earth (16 Earth radii) in the sunward direction and several times that in the anti-sunward direction. Although the region is loosely referred to as the magnetosphere, strictly speaking, this term means the (major) part of terrestrial space into which the Earth's magnetic field extends.[2]

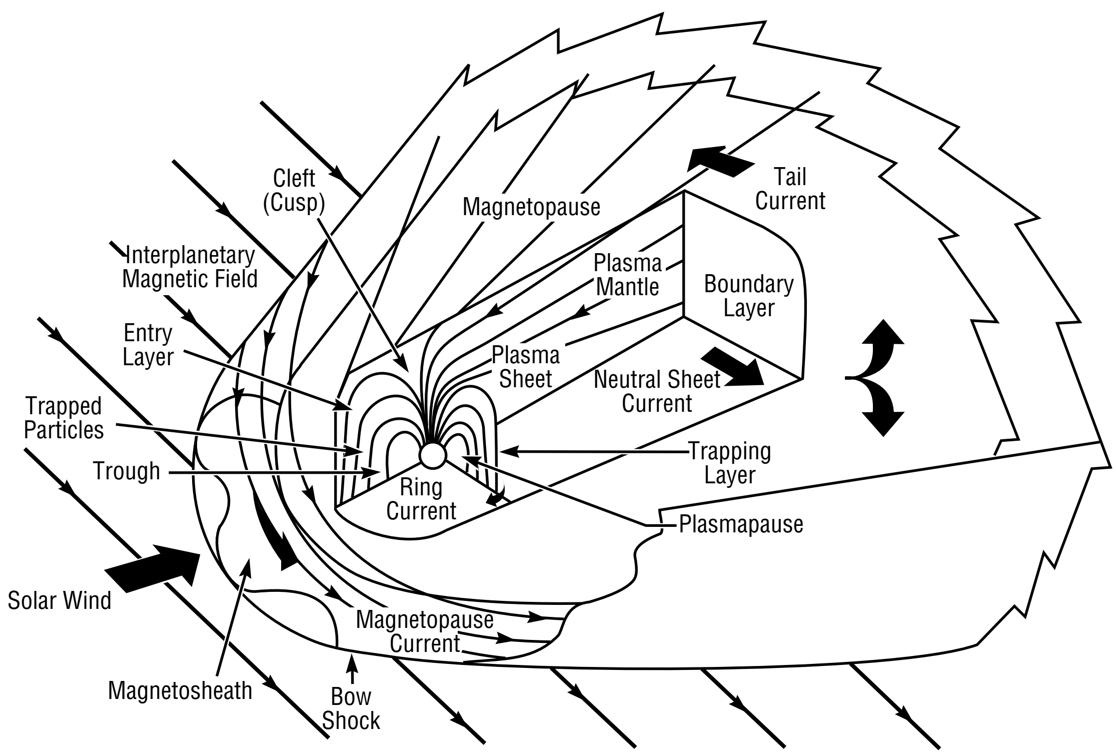

Figure 1. Schematic view of terrestrial space.[3]

Processes within terrestrial space are partially controlled by level of solar activity that varies more or less cyclically with an average period of 11 years (fig. 2). The electromagnetic radiation emitted by the Sun varies (although not much in the visible portion of the spectrum) as does the solar wind, the solar magnetic field, and the production of solar cosmic rays. Although the exact level of solar activity cannot be predicted accurately, the phase within the 11-year period can be established. In addition, plasma, radio noise, and energetic particles tend to be emitted from localized regions on the Sun's surface. These regions and some coronal features persist longer than the solar rotation period of 27 days. Since these affect the Earth only when they face it, enhanced solar activity can be estimated 27 or more days in advance.[2]

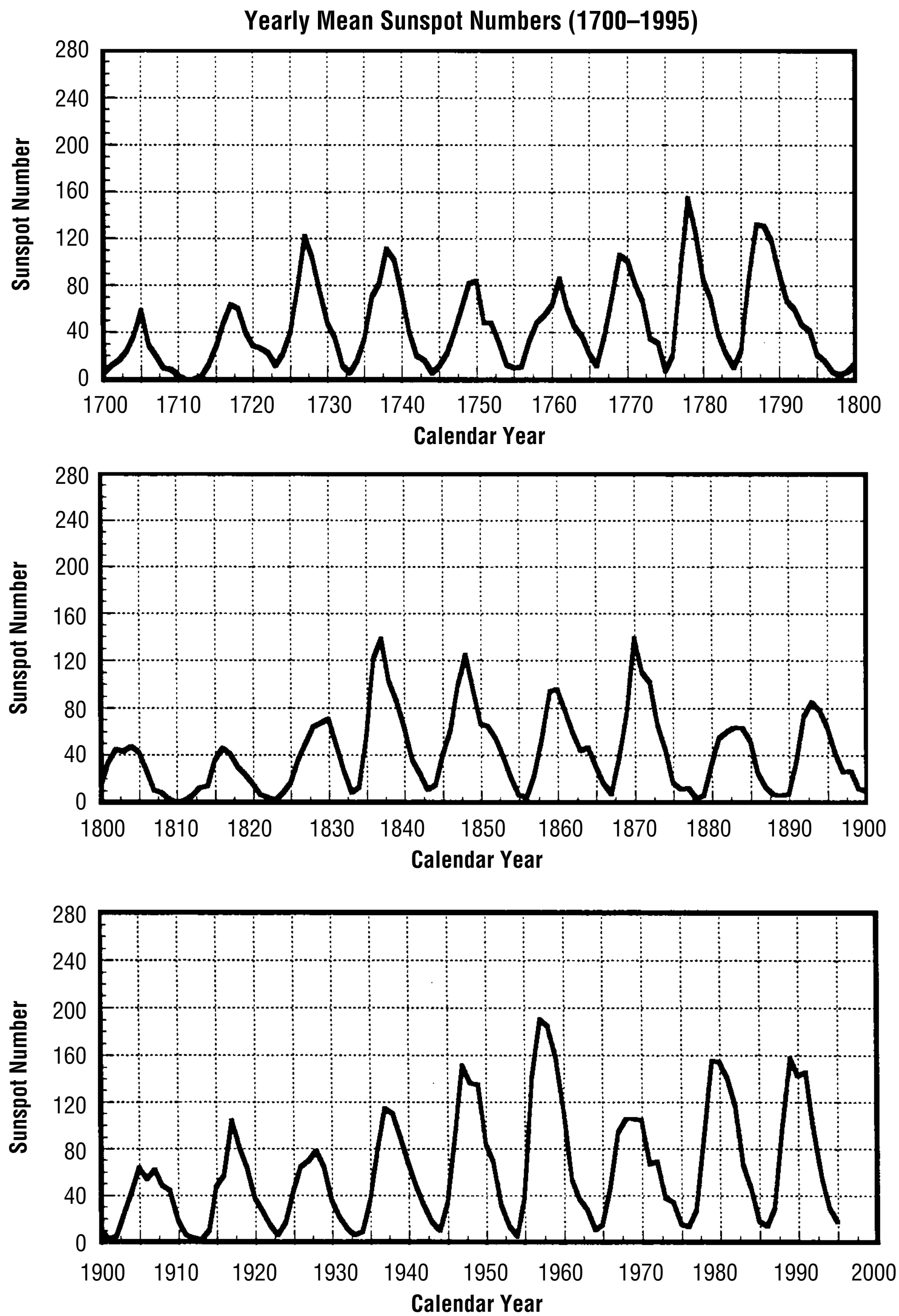

Figure 2. Solar cycle as represented by years mean sunspot number.

Despite documented scientific observations of the existence of cyclic behavior since invention of the telescope in the 17th century, the regular variation of solar activity, known as the 11-year sunspot cycle, was not discovered until the mid-19th century. Perhaps the earliest recorded physical effects of solar activity on mankind were intermittent telegraph outages in the late 1850's. Not until the 1940's were systematic scientific observations of particulate emissions from the Sun made at Earth.[4] The effects on communications, and subsequently spacecraft, have significantly increased awareness of the key role variations in solar activity play in the engineering and operation of spacecraft systems.

Elements of solar activity, solar activity influences on the space environment, solar activity effects on spacecraft, and prediction of solar activity are discussed in the following sections.

ELEMENTS OF SOLAR ACTIVITY

The Sun emits huge amounts of mass and energy—enough energy in one second to power several million cars for over a billion years. This tremendous emission of energy has important consequences to spacecraft design, development, and operation. Over short periods of time in certain locations, solar intensity can fluctuate rapidly. It is thought that a major factor causing these fluctuations is the distortion of the Sun's large magnetic field due to its differential rotation. Two of the most common indicators of locally enhanced magnetic fields are sunspots and flares. Sunspots are probably the most commonly known solar activity feature. The average sunspot number varies with a period of about 11 years. Each cycle is defined as beginning with solar minimum (time of lowest sunspot number) and lasting until the following minimum. A solar flare is a highly concentrated explosive release of energy within the solar atmosphere. Radiation from a solar flare extends from radio to X-ray frequencies. Solar flares are differentiated according to total energy released. Ultimately, the total energy emitted is the deciding factor in the severity of a flare's effects on the natural space environment.[1]

While energy is not emitted uniformly or steadily over the Sun's surface, "solar storms" are observed in which the local energy emission appears enhanced (fig. 3). These storms, which may last for many months, are manifested by dark sunspots surrounded by plages (large areas brighter than average), prominence (large volumes of dense cool gas suspended above the surface), nonuniform structures in the outer atmosphere, and a complex configuration of enhanced magnetic fields. Frequency of occurrence of this activity reaches a peak approximately every 11 years, but the magnetic fields return to the same general configuration only every 22 years. It appears that solar activity is caused by an interaction between magnetic fields and the nonuniform rotation of the Sun. The Sun's equator rotates faster than its poles, and the shearing action on the gas contorts the fields into configurations that produce activity. Although this appears feasible, many details of the formation, maintenance, and dissipation of solar activity are yet to be understood.[5]

Figure 3. Solar active region on Sun surface.[6]

Although flares are just one form of solar activity, their practical importance and intriguing, dynamic nature warrant special attention. Flares are manifested by an explosive release of high-energy radiation and, occasionally, particles from very localized areas of magnetically complex active regions. This release occurs sporadically and involves energies that are extremely large by earthly standards. Large solar magnetic fields seem to accumulate and store energy in an unstable configuration. Return to a more stable and lower-energy configuration is somehow triggered and energy rapidly released. Details of this energy buildup, storage, and release are not known. Also important, but not understood, is the mechanism by which particles are accelerated to extremely high energies and released.[7] The frequency of occurrence and magnitude of solar flare events vary as a function of solar activity (fig. 4).

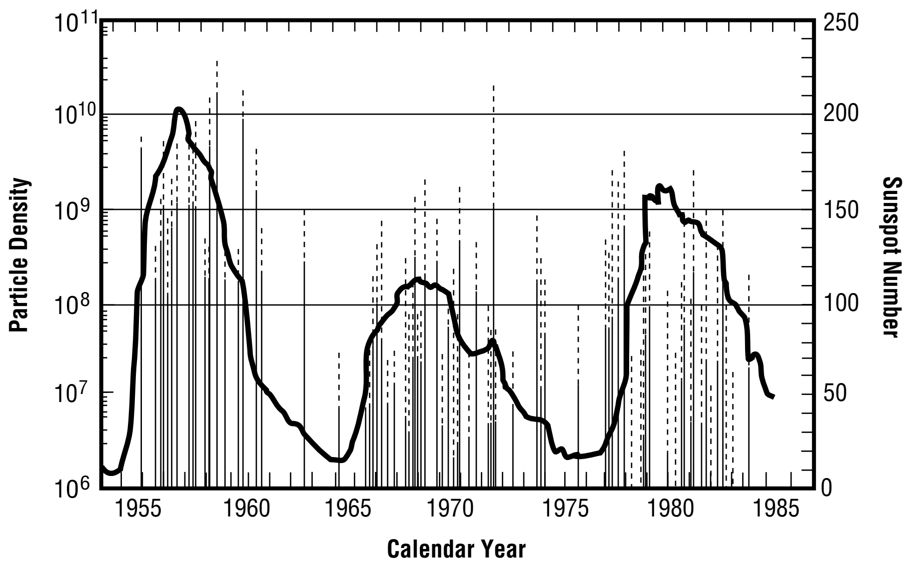

Figure 4. Variation of solar flare proton events as a function of solar activity.[1]

The cause of all forms of solar activity can be traced to convection and circulation within the Sun. The convective zone of the Sun is a giant heat engine that converts a small fraction of the outward flowing heat into convective motions, and from them into magnetic fields and hydrodynamic and hydromagnetic waves. From these phenomena arise the sunspot, prominence, flare, corona, solar wind, etc.

SOLAR ACTIVITY INFLUENCES ON SPACE ENVIRONMENT

The Sun (including its light output, magnetic configuration, and output of solar wind), magnetosphere, ionosphere, and atmosphere are a coupled physical system whose responses to changes in solar activity are pervasive and complex. Because man-made systems typically interact with a very small segment of this system, it is extremely difficult to draw a straight line between cause and effect for individual events or measurements. Figure 5 illustrates the coupled Sun-Earth system.[4] Six influences of solar activity on the natural space environment are discussed below.

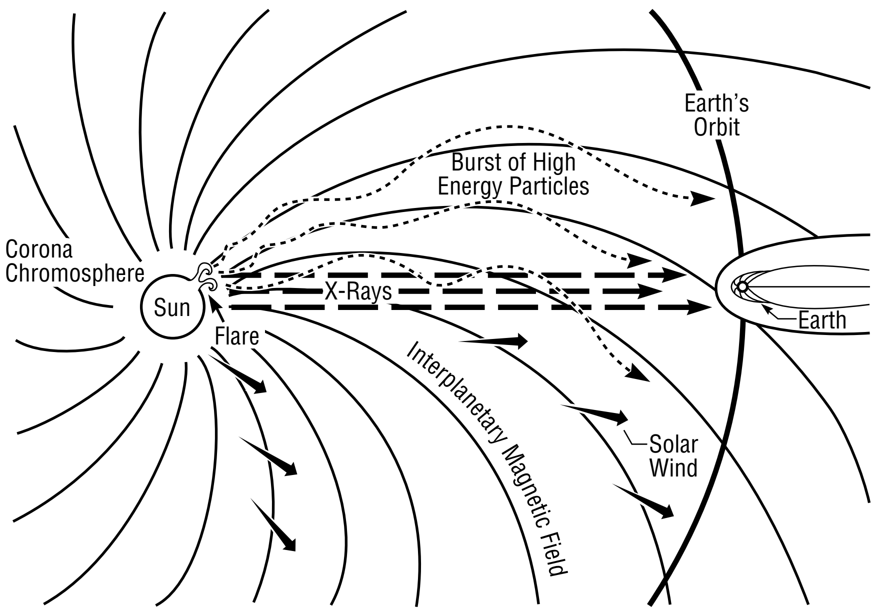

Figure 5. Polar view of interplanetary space.[4]

Solar Particle Events

One of the most direct influences of solar activity on the natural space environment is sporadic occurrence of very energetic (10 MeV to above 1 GeV) solar particle events in association with solar flares. Although solar particle events are fairly infrequent (on average, a few events per year), they represent the most energetic, tangible manifestations of solar activity. These events have important consequences for the natural space environment and spacecraft systems operating within that environment.[4]

The overall importance of an individual event depends on the maximum intensity and length of the event and relative abundance of the higher-energy component and heavy nuclei. Aside from its elemental composition, virtually all important characteristics of a solar particle event are influenced strongly by the location (longitude primarily) of the originating solar flare relative to the footprint of the interplanetary magnetic field line that is instantaneously “connected” to Earth (fig. 5).

Geomagnetic Activity

While sunspots have virtually no effect on geomagnetic activity, other solar parameters do affect the natural space environment and tend to be modulated along with sunspot numbers in an 11-year cycle. Also, the modulation amplitude of many solar parameters tracks the sunspot number fairly closely. Thus, one might expect geomagnetic activity to be modulated at the 11-year sunspot cycle. Figure 6 shows this to be so and plots yearly averages of sunspot number and index of geomagnetic activity from 1870 to 1979 (including data from solar cycles 11 to 21). The geomagnetic activity index shows a clear modulation corresponding to the 11-year sunspot cycle. However, the annual averages of geomagnetic activity do not maximize at the time of sunspot maximum (sunspot maxima are marked with arrows), nor do cyclic peaks correspond in magnitude to the amplitude of the nearest sunspot maximum. The geomagnetic index tends to have a major peak during the declining phase of the sunspot cycle and a secondary peak near the sunspot maximum. This trend is observed also in the frequency of occurrence of major geomagnetic storms.[4]

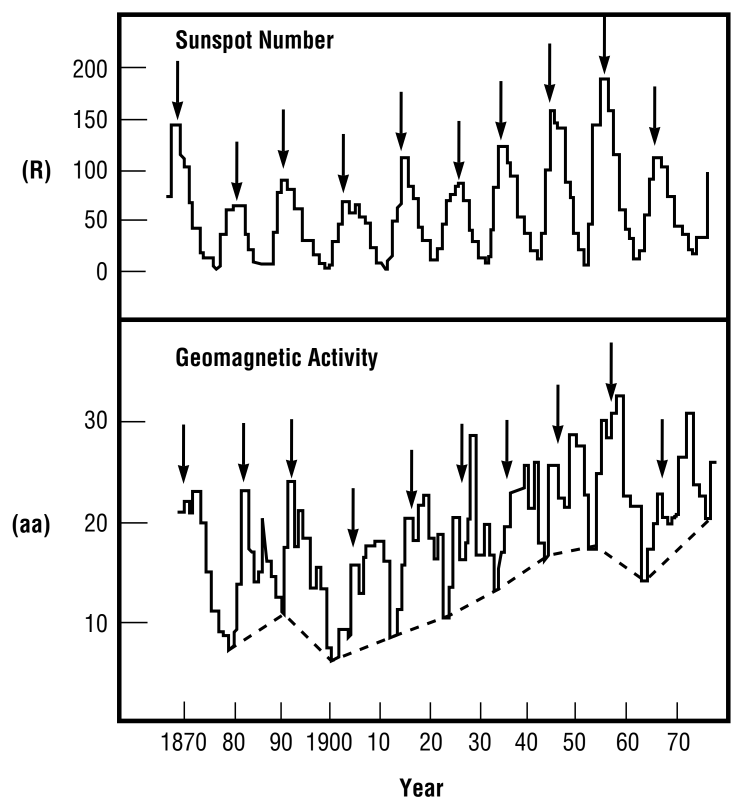

Figure 6. Annual mean of sunspot numbers and geomagnetic activity index.[4]

Illustrated in the top half of figure 7 is a huge interplanetary disturbance that struck the Earth's protective magnetic field on October 18, 1995, and produced a magnetic storm or auroral displays ("Northern Lights") that persisted for two days. A giant magnetic cloud containing hot gas from the solar corona was ejected from the Sun toward the Earth at 2.1 million miles per hour and detected by NASA's WIND spacecraft instruments half an hour before it encountered Earth.

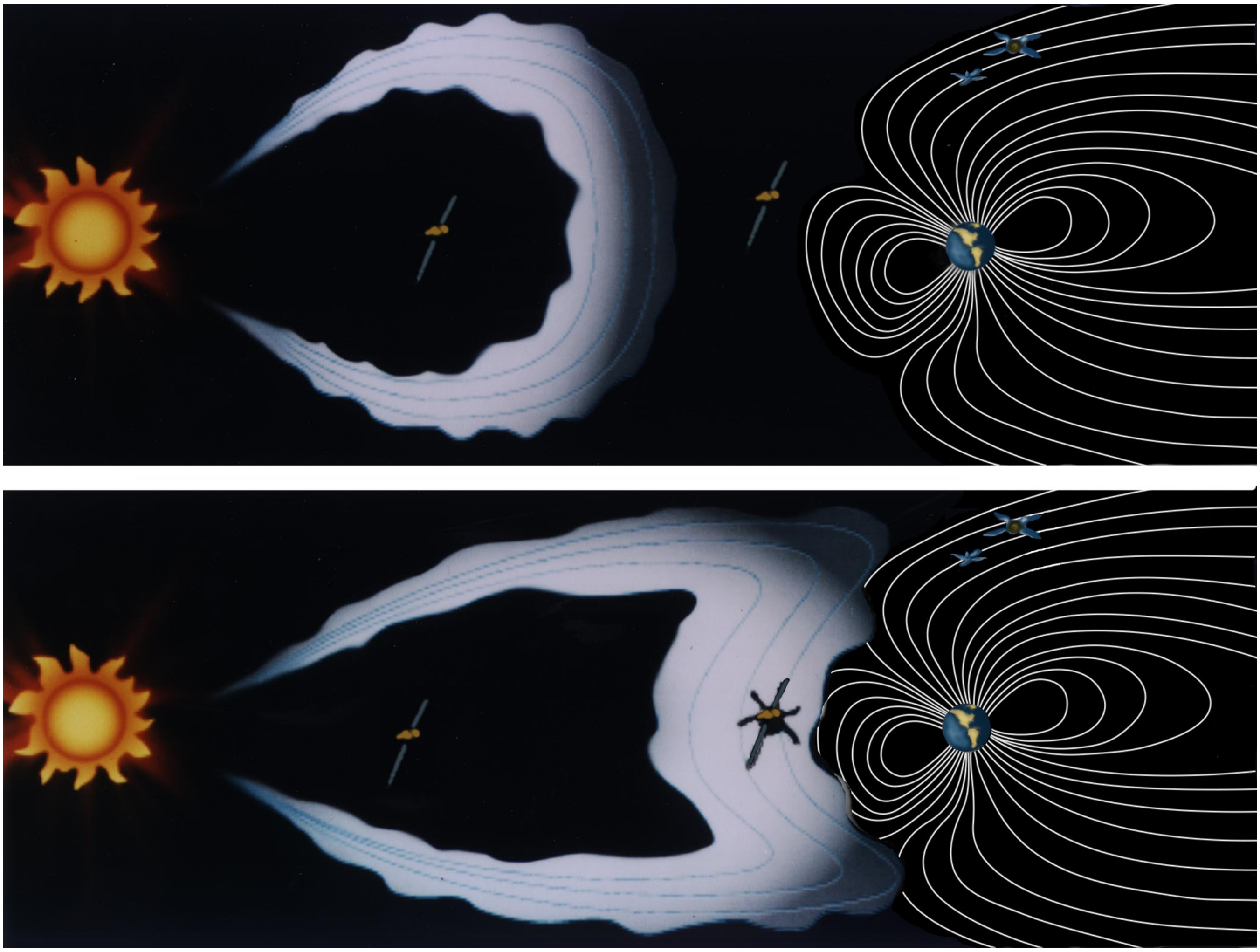

Figure 7. Interplanetary disturbance and Earth's magnetic field interaction.[8]

The second artist concept in the bottom half of figure 7 shows the magnetic cloud colliding and enveloping the Earth's magnetic field, compressing it on the day side, stretching it on the night side, and causing geomagnetic storms that can affect power grids and communication systems. In both top and bottom images, the spacecraft to the left is WIND, the one closest to Earth is GEOTAIL, and the two shown on the night side of Earth are the Russian Interball Tail Probe with its nearby daughter probe.[8]

The observed correlation between solar activity and geomagnetic activity implies that many communications and space systems could be adversely affected during and for several years after an extreme solar maximum. Note that the cited correlation has used indices of geomagnetic activity. Measurements of solar cycle dependencies on plasma parameters (i.e., temperature, density, and composition) are rare and difficult to accomplish.[4]

Neutral Atmosphere

Solar activity affects Earth's neutral atmosphere at virtually all altitudes. As one might expect, variations in the neutral atmosphere are more dramatic and occur on shorter time scales with increasing altitude. Indeed, order-of-magnitude variations in the neutral atmosphere density can occur at altitudes where low-Earth satellites orbit. These effects have significant operational consequences on satellites orbiting through low-altitude regions, space vehicles reentering the atmosphere, and systems tracking and monitoring satellites and space debris. Also, variations in composition, particularly in highly reactive constituents such as AO, can have important impacts on survivability and operation of space systems. Although solar cycle variation in AO is not significant at altitudes below about 200 km, the AO concentration at higher altitudes (500 to 800 km) can vary over the solar cycle by a factor of 1000. High concentrations of AO can react chemically with various surfaces of a spacecraft or sensor, and can lead to mass loss from external structures and degrade sensor performance.[4]

The most dominant aspect of solar variability that leads to modulation of upper atmospheric parameters is the Sun's output of radiation in the extreme ultraviolet wavelength band. All solar extreme ultraviolet flux incident on Earth's atmosphere is absorbed within the uppermost layer of the atmosphere (thermosphere). Over an 11-year solar activity cycle, the solar extreme ultraviolet emission varies by a factor of about 2 in integrated intensity (compared to <0.2 percent variability in light output in visible portion of the spectrum). This variation in irradiance can cause substantial solar cycle variations in the composition, temperature, density, and wind distribution of Earth's thermosphere.[4] Density variation is shown in figure 8.

Enhanced geomagnetic activity correlated with solar activity is another (though secondary) mechanism by which the upper atmosphere of the Earth is influenced by variations in solar activity. Geomagnetic effects of Earth's upper atmosphere tend to be isolated to the high-altitude regions and more sporadic and episodic than global effects of long-term variability in the Sun's extreme ultraviolet emission. The principal effect of geomagnetic activity on the neutral atmosphere is intense localized warming of the upper atmosphere in the polar and auroral regions. This warming is caused by kinetic heating from the precipitation of energetic charged particles and by Joule heating from enhanced ionospheric currents in the auroral zone.[4]

Ionosphere

Earth's ionosphere is a relatively thin layer of partially ionized magnetized plasma extending from about 80 to 500 km altitude. Typical plasma densities in the ionosphere range from 10^3 to 10^6 per cubic centimeter, compared with neutral densities of about 10^7 to 10^{16} per cubic centimeter. Because of strong coupling between the ionosphere and Sun, Earth's atmosphere, and magnetosphere, the phenomenology of the ionosphere is complex and under scientific investigation for years. To categorize the various physical processes that govern ionospheric structure, the ionosphere is subdivided into two or three layers in altitude, two or three zones in latitude, and separated by day or night.[4]

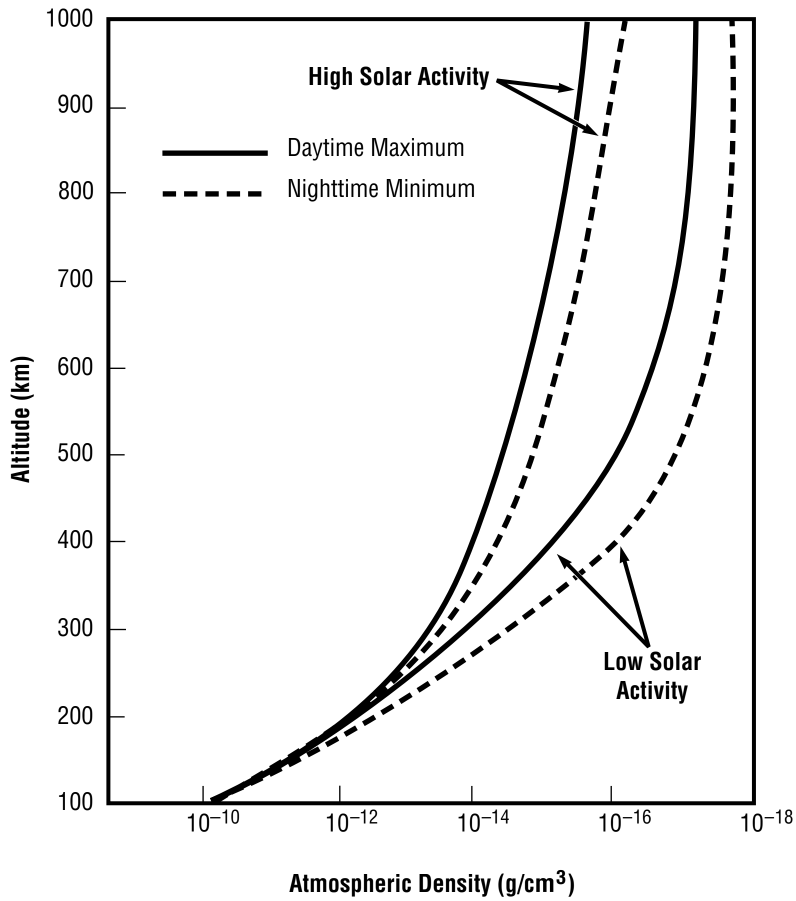

Figure 8. Typical air mass density profiles at high and low solar activity.[2]

Magnetospheric Plasmas

The high-altitude ionosphere is linked strongly to the magnetosphere by the geomagnetic field, and its variations are driven mainly by geomagnetic activity originating in the magnetosphere. Figure 9 shows a noon-midnight meridian cross section of the typical configuration of the geomagnetic field within the magnetosphere. The interaction of solar wind, which flows at supersonic speed (250 to 800 km/s) relative to Earth, with magnetosphere causes the formation of a bow shock at distances of about 20 Earth radii upstream. The region of hot compressed solar plasma between the bow shock and boundary of the magnetosphere (the magnetopause) is the magnetosheath. Size of the magnetosphere varies greatly and is determined mainly by a balance between solar wind dynamic pressure and magnetic pressure within the magnetosphere.[4]

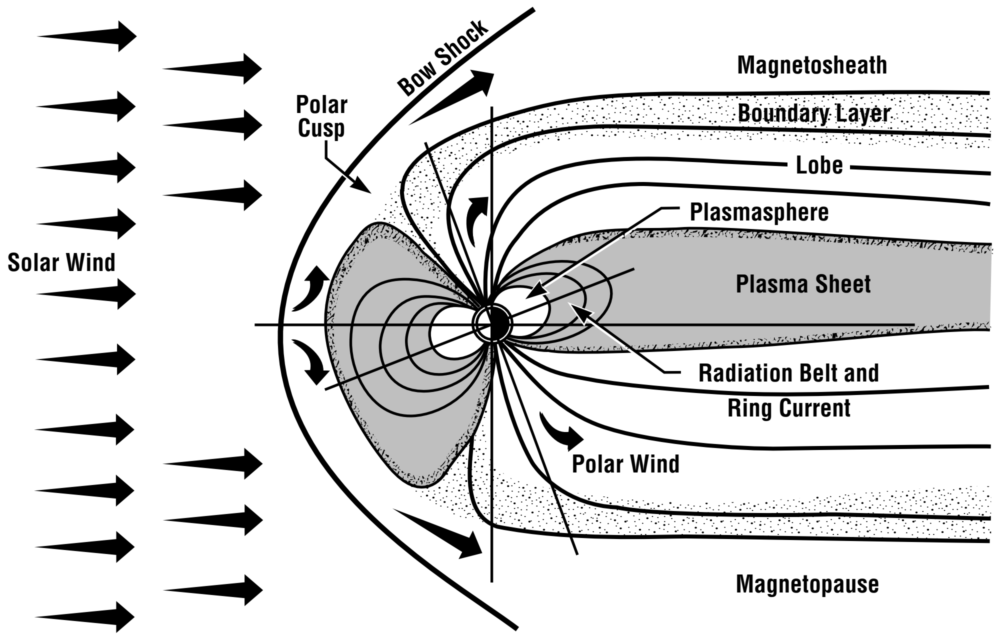

Figure 9. Meridional view of Earth's magnetosphere.[4]

Magnetospheric Energetic Particles

Variations in Earth's trapped energetic particle environment caused by solar activity are characterized by variations of geomagnetic activity. Fluxes of approximately megaelectronvolts (MeV) electrons in the outer zone of Earth's radiation belts are known to increase by two to three orders of magnitude in response to a geomagnetic storm. These flux increases can last two or three weeks following the storm. Variations of the trapped energetic electron environment maximize in the heart of the outer zone, about 3.5 Earth radii distance. Modest fluctuations are observed deeper in the radiation belts in response to the most extreme geomagnetic storms. One of the first effects of a geomagnetic storm onset is an energetic electron flux decrease. Major storms, however, produce enhanced fluxes of energetic electrons in the outer zone (internal to geosynchronous orbit). Thus, the effects of solar activity include prompt, direct effects from enhanced levels of solar ultraviolet, X rays, and energetic particles. Indirect effects of enhanced geomagnetic activity are caused by interaction between the solar wind and terrestrial magnetosphere-ionosphere-atmosphere system.[4]

SOLAR ACTIVITY EFFECTS ON SPACECRAFT

Solar activity has a critical impact on most elements within the ambient environment a spacecraft experiences. Variations in solar activity impact the upper atmosphere (thermosphere) density levels, overall thermal environment, plasma density levels, meteoroids/orbital debris levels, severity of ionizing radiation, and characteristics of the Earth's magnetic field. The solar cycle also impacts mission planning and operation activities. For example, when solar activity is high, ultraviolet radiation from the Sun heats and expands the Earth's upper atmosphere, increasing atmospheric drag and orbital decay rate of spacecraft. Solar flares, a major contributor to the overall radiation environment, can add to accumulated radiation dose levels and single event phenomena that affect electronic systems.[1]

The primary operational effect of variability of the upper atmosphere is neutral density on satellite drag. Short-term variations in density, which occur during geomagnetic events, perturb the orbital motions of satellites and lead to difficulties in tracking and cataloging objects at low-orbit altitudes. These short-term perturbations lead also to uncertainties in position for reentry of orbiting vehicles. Long-term variations in atmospheric density, such as those driven by solar cycle variations in the extreme ultraviolet irradiance, have order-of-magnitude effects on the lifetime of satellites in low-Earth orbit (LEO). Figure 10 is an example of satellite lifetime as a function of $F_{10.7}$ solar flux for circular orbit at various initial altitudes.[4]

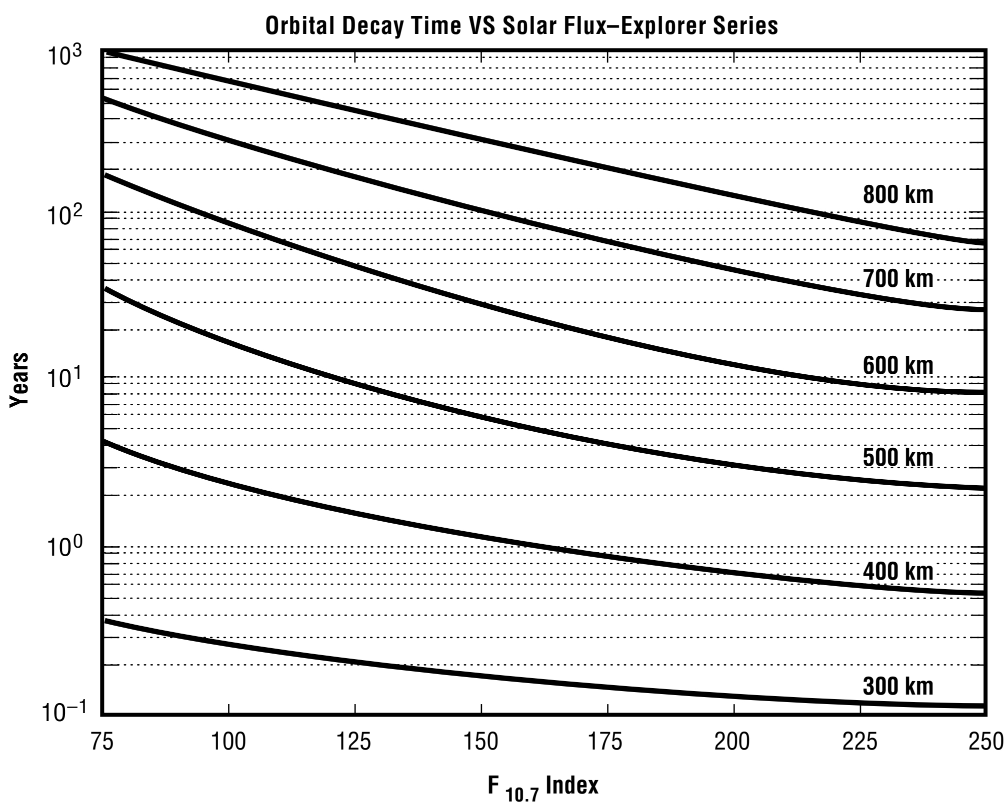

Figure 10. Satellite lifetime versus solar flux.[4]

Many spacecraft surface materials are susceptible to attack by AO, a major constituent of the LEO thermosphere region. Due to photo dissociation, oxygen varies with altitude and solar activity. Simultaneous exposure to ultraviolet radiation, micrometeoroid/debris damage, sputtering, or contamination can aggravate AO effects and lead to serious deterioration of mechanical, optical, and thermal properties of some material surfaces. A related phenomenon that may be of concern for optically sensitive experiments is spacecraft glow. Optical emissions are generated from metastable molecules excited by impact on the spacecraft surface. Investigations show that the surface acts as a catalyst, thus, intensity depends on type of surface material.[1]

During heightened solar activity, three principal elements of the natural space environment attack spacecraft with increased vigor. Ambient plasmas charge spacecraft surfaces and cause arc discharges across the vehicle. High-energy electrons penetrate a spacecraft and build high charges in insulation on coaxial lines. Protons and other charged particles disrupt computer memories or even damage the structure of semiconductor microelectronics.[4] Spacecraft damage also includes decreased power production by solar arrays, failure of sensitive electronics, increased background noise in sensors, and radiation exposure to members of the crew. Modern electronics are becoming increasingly sensitive to ionizing radiation.[1]

The geomagnetic field influences motions of particles within the Earth’s orbital environment and deflects incoming high-energy particles associated with cosmic rays. These high-energy particles may charge spacecraft surfaces, causing failure of or interference with, spacecraft systems. Due to dipole field geometry, the magnetic field strength of the Earth is lowest over the southern Atlantic Ocean. This causes a higher concentration of trapped radiation in the region. In the vicinity of this anomaly a spacecraft may encounter electronics “upsets” and instrument interference. An accurate depiction of the geomagnetic field is needed to properly size magnetic torquers used in the guidance, navigation, and control system of a spacecraft.[1]

Geomagnetic storms, disturbances in the geomagnetic field lasting one or more days, may affect orbiting spacecraft. During a geomagnetic storm large numbers of charged particles are dumped from the magnetosphere into the Earth’s atmosphere. These particles ionize and heat the atmosphere through collisions. The heating is first observed minutes to hours after the magnetic disturbance begins. The effects of geomagnetic heating extend from 300 km to well over 1000 km and may persist for 8 to 12 hours after the disturbance ends.[1]

Orbiting through this ionized portion of the atmosphere, a spacecraft may be subjected to an unequal flux of ions and electrons and develop an induced charge. Plasma flux to the spacecraft surface can charge the surface and disrupt operation of electrically biased instruments. In LEO vehicles travel through dense but low energy plasma that negatively charges them because their orbital velocity is greater than the ion thermal velocity but slower than the electron thermal velocity. Thus, electrons can impact all surfaces; ions can impact only ram surfaces. LEO spacecraft have charged to thousands of volts but charging at geosynchronous orbits is a greater concern, i.e., biased surfaces, such as solar arrays, can affect the floating potential. Magnitude of charge depends on the type of grounding configuration used. Spacecraft charging may cause biasing of instrument readings, arcing that upsets sensitive electronics, increased current collection, retraction of contaminants, ion sputtering that accelerates erosion of materials, and other electrical disturbances.[1]

The most severe spacecraft surface-charging events (and resulting electrostatic discharges) tend to occur in the midnight-to-dawn local time sector, when spacecraft encounter high fluxes of hot drifting plasma sheet electrons. The probability of occurrence and severity of spacecraft charging events are directly correlated with periods of enhanced geomagnetic energization. Severe charging events tend to occur during equinox, when geosynchronous vehicles enter and exit Earth eclipse once each day (geomagnetic storms also show seasonal modulation). In sunlight photoelectron flux emitted from the spacecraft tends to balance current from the surrounding plasma. During eclipse a spacecraft cannot emit a photoelectron flux to balance the hot electron current from plasma, thus, electrical charging of the vehicle to several kilovolts is possible. Upon exiting the eclipse various surface materials discharge at different rates and create the possibility of large differential potentials and discharges between external spacecraft components.[4] Table 1 gives additional consequences of major solar activity events.

Table 1. Examples of some consequences of major solar activity events[6]

Earth and Space Systems:

- "Hits" on deep space satellites (e.g., Magellan and Galileo)
- Failures, serious power panel degradation, and lesser problems on geostationary satellites
- Navigation satellite signal problems from half-geostationary orbit
- Low altitude satellites tumbling and sensor problems

Energetic Particles:

- Degradation of photo-sensitive satellite components (star trackers and power panels)
- Deep dielectric charging of satellite parts
- Surface charging on satellites
- Single Event Upsets (SEU's)
- "Flashes" in astronauts' eyes
- Radiation exposure on high-altitude aircraft

Geomagnetic Field:

- Great magnetic storms during some events and not others
- Large auroral electrojet substorms during quiet midlatitude conditions

PREDICTION OF SOLAR ACTIVITY

Solar activity effects on spacecraft include orbital lifetime, materials, control, communications, charging, thermal, shielding, power, particle impacts, etc. The optimum design for a spacecraft would be to operationally accommodate the natural space environment resulting from the most intense solar activity conditions expected during its lifetime. Since the maximum solar activity that may occur is an unknown, this is not possible. Even if one did know, it would not be economically or engineeringly feasible to build such a spacecraft. Thus, while deriving the best practical design requirements for the natural environment, it is still operationally important to obtain the best predictions possible, short- and long-term, of anticipated environmental conditions due to solar activity.

Given the resources available, predictors of solar activity and the natural space environment do a commendable job. Present predictions, however, are often insufficient for customers to take specific mitigation actions or make specific planning decisions. Requirements for predictions, alerts, and warnings are established by the users of these services. Few current requirements are fully met; some are not met at all. Nowcasts refer to the fusion of all available observations into a coherent and realistic representation of the state of the natural space environment at the time of the observations. Synchronizing and merging the diverse observational data sets pose significant scientific and technical challenges. Sophisticated, physics-based models are needed to fill areas with no observations. Today's solar activity and natural space models are just starting to approach this goal.[9] For example, in much the same way as meteorologists have developed criteria for probable tornadic activity within the Earth's atmosphere, solar scientists are making progress toward predicting sites for flare activity on the Sun. As more is learned about the Sun's behavior, realistic modeling and accurate predictions of the Sun's future behavior can be expected.

Correlation between solar activity and disturbances in the near-Earth magnetosphere, ionosphere, and atmosphere is well documented. Unfortunately, very few long-term quantitative predictions can be made regarding the expected effects of an extreme solar maximum on the near-Earth environment or complex systems operating in that environment. Scientific knowledge and practical experience gained have yet to yield an adequate state-of-the-art capability for short-term predictions of occurrence of geomagnetic storms based on real-time observations of solar activity. However, progress is being made in this area and a number of important qualitative predictions are made with high confidence.[4]

The regular modulation of the solar cycle has been repeated sufficiently for many investigators to identify patterns in the activity cycles and form the basis for statistical predictions of future solar activity. Unfortunately, the cycle-to-cycle coherence in magnitude of solar activity is insufficient to yield predictive capabilities with high confidence levels. Furthermore, evidence exists for very long-term trends in solar activity, which leads some to believe they are viewing a continually changing Sun. Perhaps most importantly, virtually all predictive capabilities published to date (with exception of a few techniques based on the solar model) are statistically based rather than physically based; they rely on observed (statistical) patterns in the data rather than a quantitative understanding of the physical mechanisms that cause modulation of solar activity.[4]

At present, no reliable short- or long-range methods of predicting solar activity exist. The difficulty is illustrated by the wide range of predictions made for the last solar cycle and those developing for the upcoming cycle. Because of the wide range of predictions, spanning nearly the full extent of observed sunspot numbers, one would expect some of the techniques to yield by pure chance the correct value.[10] One test, however, does not prove that a deterministic method will work in the future. Due to the importance of solar activity for spacecraft design and operation, the search for more reliable physically based prediction models and statistical models with better confidence bounds should continue vigorously.

Variability of the solar cycle has been statistically described using a proxy parameter, the 10.7-cm solar radio flux ($F_{10.7}$). The Environments Team of the Marshall Space Flight Center Electromagnetics and Aerospace Environments Branch estimates and publishes a monthly solar activity memorandum that gives intermediate (months) and long (years) range estimates of the 13-month smoothed value for both the 10.7-cm solar radio flux and the geomagnetic activity index (A_p) with associated confidence bounds. This information is provided primarily for use as input data for upper atmospheric models to insure compatibility in calculations made for spacecraft orbital lifetime predictions.

CONCLUSION

For optimum efficiency and effectiveness, definition of the flight environment is important very early in the design cycle of a spacecraft. From experience, the earlier the environments specialist becomes involved in the design process, the less potential exists for negative environmental impacts (redesign, work-arounds, etc.) on the program. Key steps in defining solar activity and the role it plays in the space environment definition and interpretation for a particular program include the following:[1]

- Definition of the solar environment is critical. Since definition depends on orbit of the spacecraft and phase of the solar cycle (solar activity), environmental effects should be reviewed prior to final orbit selection.

- Determination of environmental limiting factors is next. Not all effects of the space environment critically impact a particular mission. The environments specialist presents environmental limiting factors and offers design or operation solutions for a program. This requires a close working relationship among the environments specialist, design team, and program management. Once the limiting factors are determined, trade studies are usually required to establish the appropriate flight environment.

- Coordination of environmental requirements follows. After definition of the space environment and limiting factors comes establishing a coordinated set of natural space environment requirements compatible with the solar activity influences. These requirements are derived during the definition phase after much interaction among the designers, development engineering staff, environments specialists, and program management.

- Interpretation of these requirements by the environments specialist ensures that the solar activity effects on the space environment design requirements are understood throughout all phases of a spacecraft program.

This primer provides an overview of solar activity and its effect on spacecraft design, development, and operation. An understanding of solar activity and its effects on the space environment enables program management and space vehicle designers and operators to more effectively minimize program risks and costs, optimize design quality, and achieve mission objectives. Questions or comments should be directed to the MSFC Electromagnetics and Aerospace Environments Branch, Steven D. Pearson, 205–544–2350.

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APPENDIX

NATURAL SPACE ENVIRONMENTS

	DEFINITION	PROGRAMMATIC ISSUES	MODELS/DATABASES
NEUTRAL THERMOSPHERE	Atmospheric density, Density variations, Atmospheric composition (Atomic Oxygen), Winds	GN&C system design, Materials degradation/ surface erosion (atomic oxygen fluences), Drag/decay, S/C lifetime, Collision avoidance, Sensor pointing, Experiment design, Orbital positional errors, Tracking loss	Jacchia/MET, MSIS, LIFTIM, upper atmospheric wind models
THERMAL ENVIRONMENT	Solar radiation (albedo and OLR variations), Radiative transfer, Atmospheric transmittance	Passive and active thermal control system design, Radiator sizing/material selection, Power allocation, Solar array design	ERBE database, ERB database, NIMBUS database ISSCP database, Climate models, General Circulation Models (GCM's)
PLASMA	Ionospheric plasma, Auroral plasma, Magnetospheric plasma	EMI, S/C power systems design, Material determination, S/C heating, S/C charging/arcing	International Reference Ionosphere Models, NASCAP/LEO, NASCAP/GEO, POLAR
METEOROIDS AND ORBITAL DEBRIS	M/OD flux, Size distribution, Mass distribution, Velocity distribution, Directionality	Collision avoidance, Crew survivability, Secondary ejecta effects, Structural design/ shielding, Materials/solar panel deterioration	Flux models
SOLAR ENVIRONMENT	Solar physics and dynamics, Geomagnetic storms, Solar activity predictions, Solar/geomagnetic indices, Solar constant, Solar spectrum	Solar prediction, Lifetime/drag assessments, Reentry loads/heating, Input for other models, Contingency operations	MSFC EL Laboratory model, NOAA prediction data, Statistical models, Solar database
IONIZING RADIATION	Trapped proton/electron radiation, Galactic cosmic rays (GCR's), Solar particle events	Radiation levels, Electronics/parts dose, Electronics/single event upset, Materials dose levels, Human dose levels	CREME, AE–8MIN, AE–8MAX, AP–8MIN, AP–8MAX, Radbelt, Solpro, SHIELDOSE
MAGNETIC FIELD	Natural magnetic field	Induced currents in large structures, Locating South Atlantic Anomaly, Location of radiation belts	IGRF85, IGRF91
GRAVITATIONAL FIELD	Natural gravitational field	Orbital mechanics/tracking	GEM-T1, GEM-T2
MESOSPHERE	Atmospheric density, Density variations, Winds	Re-entry, Materials selection, Tether experiment design	Earth-GRAM 95, UARS database, Mars-GRAM 3.34

Figure A-1. A breakout of the natural space environments and typical programmatic concerns.

SPACE ENVIRONMENT EFFECTS

	SPACE ENVIRONMENTS			
SPACECRAFT SUBSYSTEMS	**Neutral Thermosphere**	**Thermal Environment**	**Plasma**	**Meteoroids/Orbital Debris**
Avionics		Thermal Design	Upsets due to EMI from Arcing, S/C Charging	EMI Due to Impacts
Electrical Power	Degradation of Solar Array Performance	Solar Array Designs, Power Allocations, Power System Performance	Shift in Floating Potential, Current Losses, Reattraction of Contaminants	Damage to Solar Cells
GN&C/Pointing	Overall GN&C/Pointing System Design		Torques due to Induced Potential	Collision Avoidance
Materials	Materials Selection, Material Degradation	Material Selection	Arcing, Sputtering, Contamination Effects on Surface Properties	Degradation of Surface Optical Properties
Optics	S/C Glow, Interference with Sensors	Influences Optical Design	Reattraction of Contaminants, Change in Surface Optical Properties	Degredation of Surface Optical Properties
Propulsion	Drag Makeup/Fuel Requirement		Shift in Floating Potential Due to Thruster Firings Making Contact with the Plasma	Collision Avoidance, Additional Shielding Increases Fuel Requirement, Rupture of Pressurized Tanks
Structures		Influences Placement of Thermally Sensitive Surfaces, Fatigue, Thermally Induced Vibrations	Mass Loss From Arcing and Sputtering, Structural Size Influences S/C Charging Effects	Structural Damage, Shielding Designs, Overall S/C Weight, Crew Survivability
Telemetry, Tracking, & Communications	Possible Tracking Errors, Possible Tracking Loss		EMI Due to Arcing	EMI Due to Impacts
Thermal Control	Reentry Loads/Heating, Surface Degradation due to Atomic Oxygen	Passive and Active Thermal Control System Design, Radiator Sizing, Freezing Points	Reattraction of Contaminants, Change in absorptance/ emittance properties	Change in Thermal/Optical Properties
Mission Operations	Reboost Timelines, S/C Lifetime Assessment	Influences Mission Planning/ Sequencing	Servicing (EVA) Timelines	Crew Survivability

Figure A-2. Space environment effects on spacecraft subsystems (page 1 of 2).

SPACE ENVIRONMENT EFFECTS

	SPACE ENVIRONMENTS				
SPACECRAFT SUBSYSTEMS	**Solar Environment**	**Ionizing Radiation**	**Magnetic Field**	**Gravitational Field**	**Mesosphere**
Avionics	Thermal Design	Degradation: SEU's, Bit Errors, Bit Switching	Induced Potential Effects		
Electrical Power	Solar Array Designs, Power Allocations	Decrease in Solar Cell Output	Induced Potential Effects		
GN&C/Pointing	Influences Density and Drag, Drives Neutrals, Induces Gravity Gradient Torques		Sizing of Magnetic Torquers	Stability & Control, Gravitational Torques	Effect on GN&C for Re-entry
Materials	Solar UV Exposure Needed for Material Selection	Degradation of Materials			Degradation of Materials Due to Atmospheric Interactions
Optics	Necessary Data for Optical Designs	Darkening of Windows and Fiber Optics			
Propulsion	Influences Density and Drag			Influences Fuel Consumption Rates	
Structures	Influences Placement of Thermal Sensitive Structures		Induces Currents in Large Structures	Propellant Budget	Tether Structural Design
Telemetry, Tracking, & Communications	Tracking Accuracy, Influences Density and Drag		Locating South Atlantic Anomaly	May Induce Tracking Errors	
Thermal Control	Influences Reentry Thermal Loads/Heating				
Mission Operations	Mission Timelines, Mission Planning	Crew Replacement Timelines			

Figure A-2. Space environment effects on spacecraft subsystems (page 2 of 2).